IS IT SUSY

Joseph Lykken
Fermilab

BROOKHAVEN FORUM, 26-28 MAY, 2010

A. Datta, G. Kane, M. Toharia, hep-ph/0510204

IS IT SUSY?

受入
90-7-95
高エ研図書室

IS HINCHLIFFE'S RULE TRUE? *

Boris Peon

Abstract

Hinchliffe has asserted that whenever the title of a paper is a question with a yes/no answer, the answer is always no. This paper demonstrates that Hinchliffe's assertion is false, but only if it is true.

Outline

- SUSY who?
- problems with SUSY models
- who is the SUSY dark matter?
- SUSY look-alikes
  - UED
  - Little Higgs
- missing energy look-alikes at the LHC
  - model-independent extraction of masses, charges, spins
  - model discrimination around the moment of discovery

SUSY who?

- Supersymmetry (SUSY) is a not a model
- It is a framework for an infinite number of models whose (only?) common feature is (broken) extended space-time symmetry
- SUSY is a “complete” framework, addressing everything from cosmology to unification to precision observables to LHC collisions
- “Anything discovered at the LHC will be called supersymmetry”

SUSY is only one of >=6 BSM frameworks

BSM frameworks

- Terascale supersymmetry (SUSY)
- PNGB Higgs
- New strong dynamics
- Flat extra dimensions
- Warped extra dimensions*
- Hidden valleys

J.L., arXiv:1005.1676

D. Morrissey, T. Plehn, T. Tait, arXiv:0912.3259

and probably more, plus hybrids of the above...

*See the review by H. Davoudiasl, S. Gopalakrishna, E. Ponton, J. Santiago, arXiv:0908.1968

SUSY who?

- Supersymmetry is a (possibly) unique physical extension of Poincare space-time symmetry
- But SUSY must be broken
- There are many possible breaking mechanisms
- And there are many possible mechanism to “mediate” SUSY breaking to the Standard Model particles

SUSY who?

- **Gravity mediation: SUSY breaking mediated by Planck-scale-suppressed couplings**

mSUGRA, anomaly mediation, stringy models,...

- **Gauge mediation: SUSY breaking mediated by loops containing heavy “messenger” fields**

minimal GMSB, metastable GMSB,...

- **Bulk mediation: We live on a “brane” in a larger (“bulk”) extra dimensional space; SUSY is broken on a different brane**

gaugino mediation, radion mediation,...

Can also classify according to the particle content and/or how many independent SUSY breaking parameters appear in the Standard Model sector;

MSSM, CMSSM, pMSSM, NMSSM, nMSSM...

A modern review: D. Chung, L. Everett, G. Kane, S. King, J.L., L-T Wang, hep-ph/0312378

problems with SUSY models

- **Why is the Z mass so light?**

$$
\begin{aligned}
M_Z^2 \quad = \quad & -1.8\mu^2(\text{UV}) + 5.9M_3^2(\text{UV}) - 0.4M_2^2(\text{UV}) - 1.2m_{H_U}^2(\text{UV}) \\
& +0.9m_{Q_3}^2(\text{UV}) + 0.7m_{U_3}^2(\text{UV}) - 0.6A_t(\text{UV})M_3(\text{UV}) \\
& -0.1A_t(\text{UV})M_2(\text{UV}) + 0.2A_t^2(\text{UV}) + 0.4M_2(\text{UV})M_3(\text{UV}) + \ldots
\end{aligned}
$$

this is a "soft" problem, but affects all terascale SUSY models

problems with SUSY models

- **The "mu problem": Why is the mass scale of the supersymmetric mu parameter related to the effective scale of SUSY breaking and of EWSB?**

$$\mu H_u H_d$$

$$\begin{aligned} M_Z^2 \quad = \quad & -1.8\mu^2(\text{UV}) + 5.9M_3^2(\text{UV}) - 0.4M_2^2(\text{UV}) - 1.2m_{H_U}^2(\text{UV}) \\ & +0.9m_{Q_3}^2(\text{UV}) + 0.7m_{U_3}^2(\text{UV}) - 0.6A_t(\text{UV})M_3(\text{UV}) \\ & -0.1A_t(\text{UV})M_2(\text{UV}) + 0.2A_t^2(\text{UV}) + 0.4M_2(\text{UV})M_3(\text{UV}) + \ldots \end{aligned}$$

this is a "soft" problem, but affects all terascale SUSY models

-- might be easier to solve in gravity mediation?

problems with SUSY models

- The “flavor problem”: Why doesn’t SUSY breaking introduce new large sources of flavor (and CP) violation, detectable at your favorite B factory etc?

    - But perhaps we are starting to see some SUSY flavor violation...

    - See the next talk by M. Neubert

this is a “soft” problem, but affects most terascale SUSY models

-- naturally explained in gauge mediation

problems with SUSY models

- Why is the Higgs so heavy?
    - For SUSY models with minimal Higgs sectors, the Higgs "should have been" discovered at LEP
    - Much recent activity on SUSY models with nonminimal Higgs sectors, such that either
        - The SM-like SUSY Higgs boson gets heavier, or
        - The SM-like SUSY Higgs boson is hidden from LEP

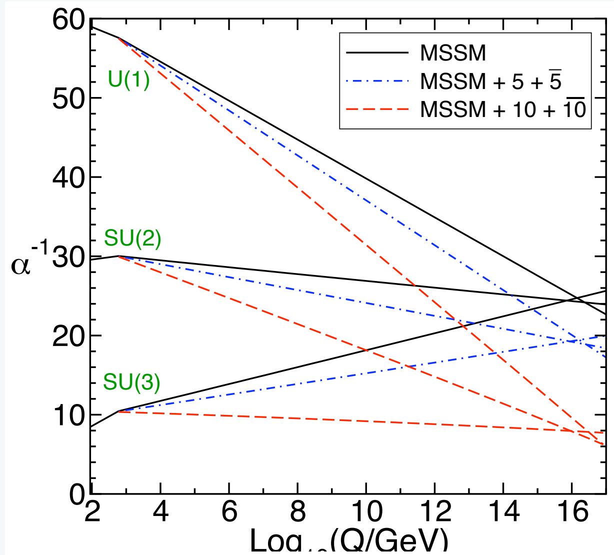
R. Dermisek and J. Gunion, arXiv:0705.4387, arXiv:0911.2460, arXiv:1002.1971

worrisome, but not a generic problem of terascale SUSY models

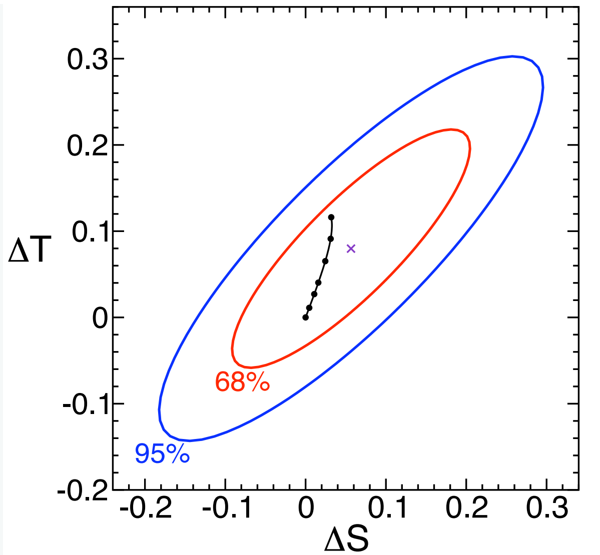
SUSY models with extra stuff

- For example, one way to increase the Higgs mass in SUSY without causing other problems is to introduce new heavy vectorlike matter:

$$W = M_\Phi \Phi\overline{\Phi} + M_\phi \phi\overline{\phi} + kH_u\Phi\overline{\phi} - hH_d\overline{\Phi}\phi,$$



doesn't have to spoil gauge coupling unification



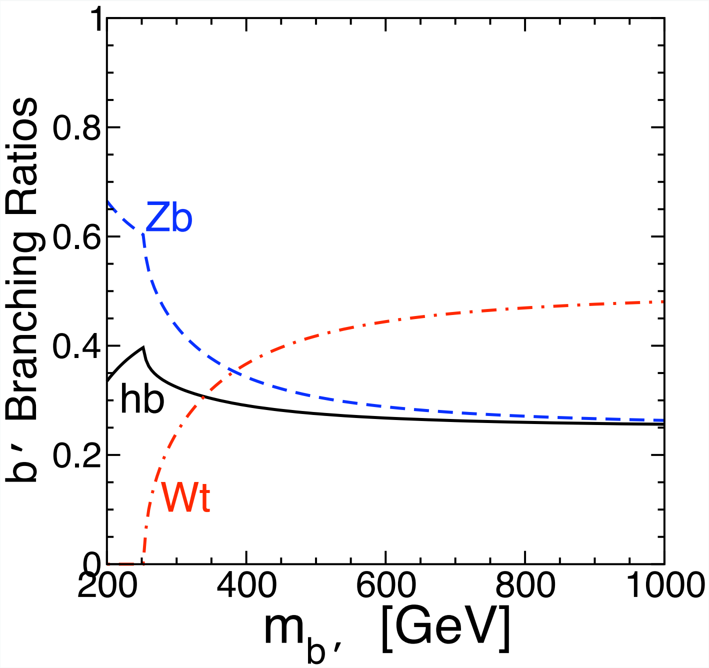
doesn't conflict with precision electroweak data

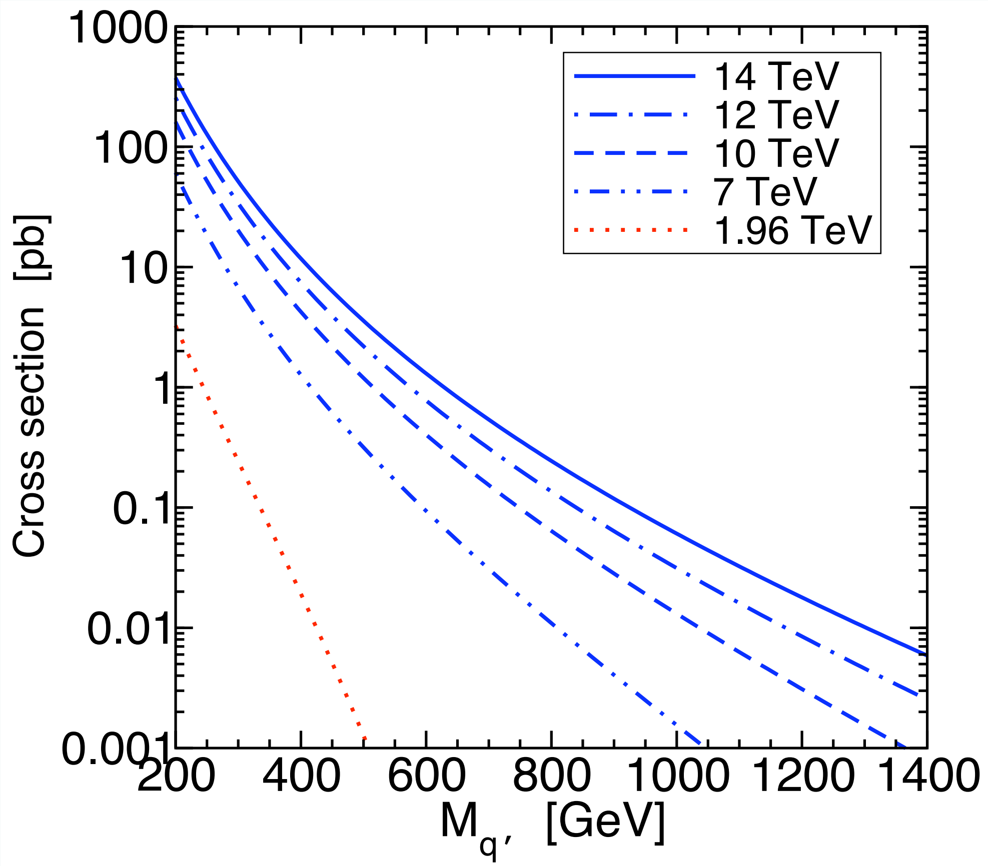
S. Martin, arXiv:0910.2732

new heavy fermions at LHC

- the Tevatron sensitivity falls off a cliff for masses above ~300 GeV
- LHC cross sections at 7 TeV could be > 1 pb

S. Martin, arXiv:0910.2732

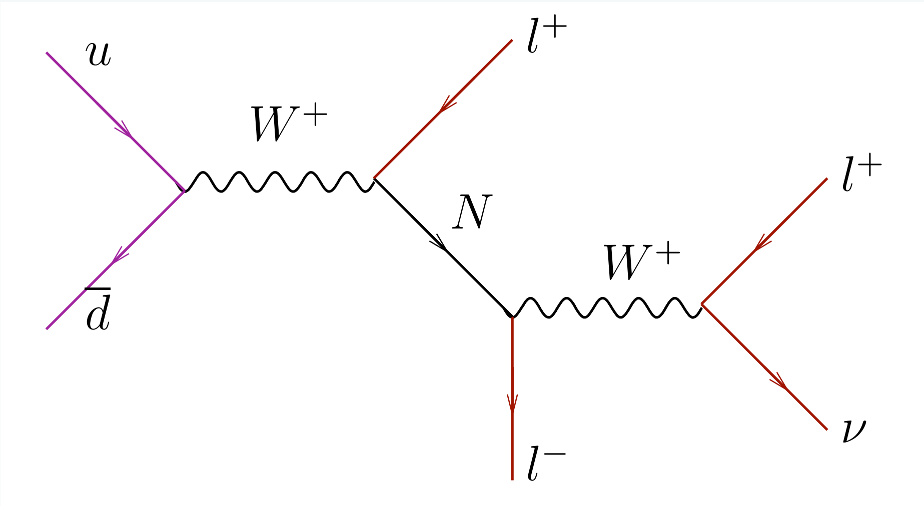




SUSY “add-ons” could also be the first things discovered

new heavy fermions at LHC

- **or perhaps your SUSY extension has a 500 GeV RH neutrino and a 1.5 TeV W_R**



B. Dev, R. Mohapatra, arXiv:0910.3924, arXiv:1003.6102

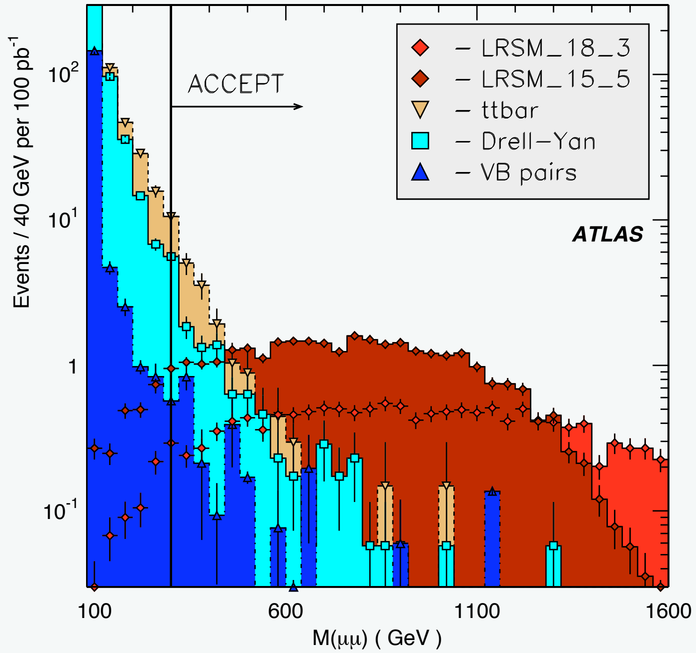


Figure 6: LRSM analysis. The distributions of S_T (top) and $M(\ell\ell)$ (bottom) for signals and backgrounds normalized to 100pb^{-1} of integrated pp luminosity after baseline selection in the dimuon analysis.

who is the SUSY dark matter?

- Most SUSY models assume (by fiat) an exactly conserved R-parity
- Then the lightest superpartner (LSP) is stable, and could be dark matter
- At the LHC, we also care about who is the NLSP
- And perhaps R-parity is not exactly conserved or more complicated...

K. Agashe, D. Kim, M. Toharia, D.G.E. Walker, arXiv:1003.0899

who is the SUSY dark matter?

Many viable LSP dark matter candidates:

- **spin 1/2 Majorana bino-like neutralino**
- **wino-like neutralino.**
- **higgsino-like neutralino**
- **spin 3/2 gravitino (with some work)**
- **spin 0 sneutrino (with more work)**
- **spin 1/2 singlino**
- **spin 1/2 axino**

Even assuming SUSY is right, a complicated story to sort out!!

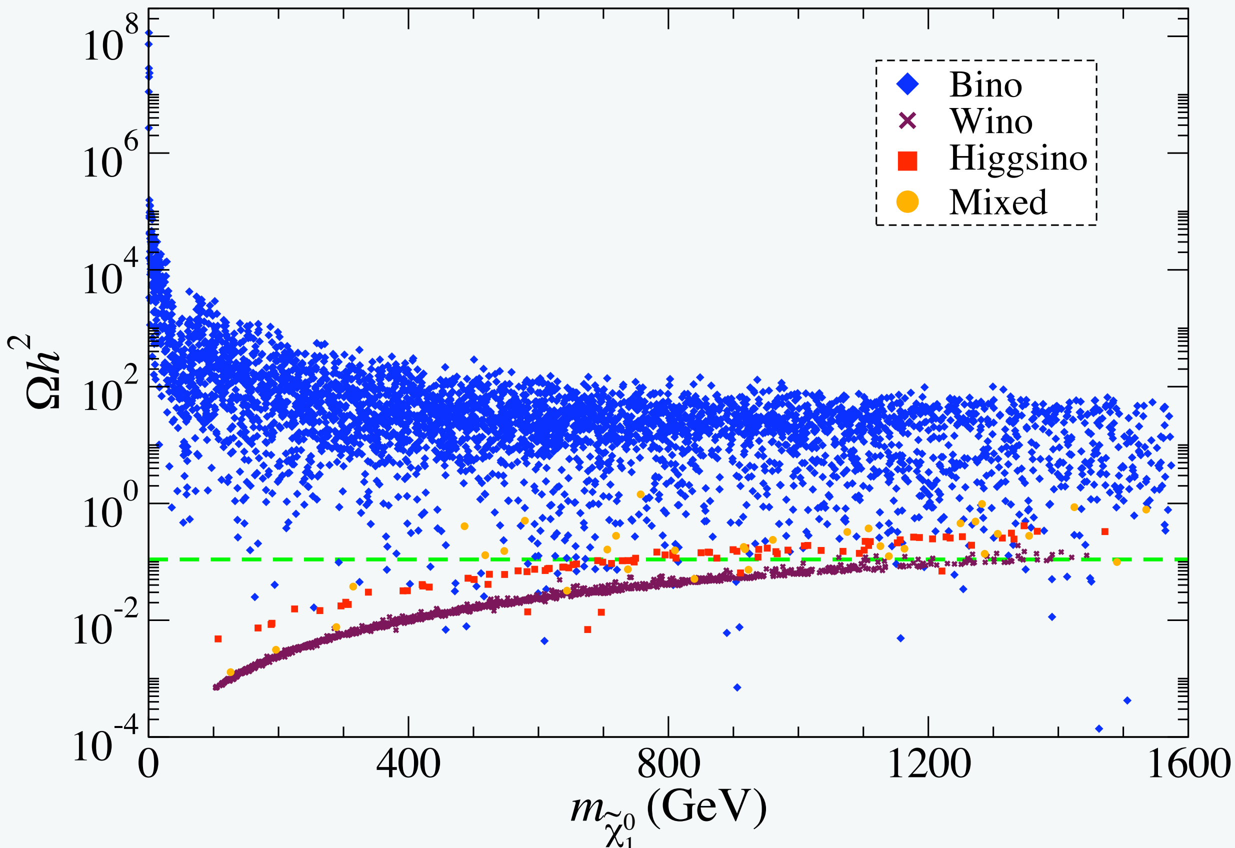
who is the SUSY dark matter?

But "everybody knows" that the dark matter is a bino-like neutralino!?

H. Baer, A. Box, H. Summy, arXiv:10052215

J. Gainer, J. Hewett, T. Rizzo, arXiv:0812.0980

Let's scan the 19 parameter pMSSM, a reasonably general parameterization of SM sector + superpartners with minimal particle content:

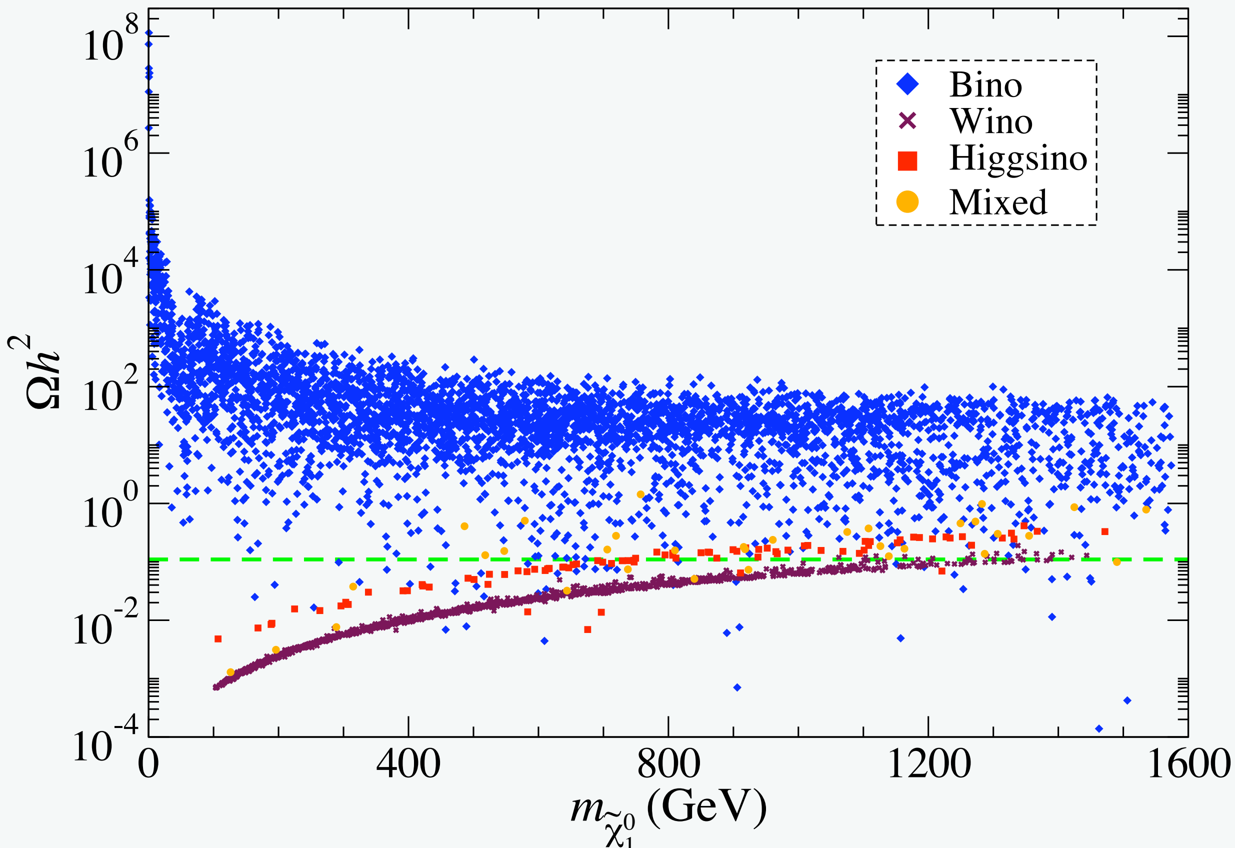


who is the SUSY dark matter?

But “everybody knows” that the dark matter is a bino-like neutralino!?

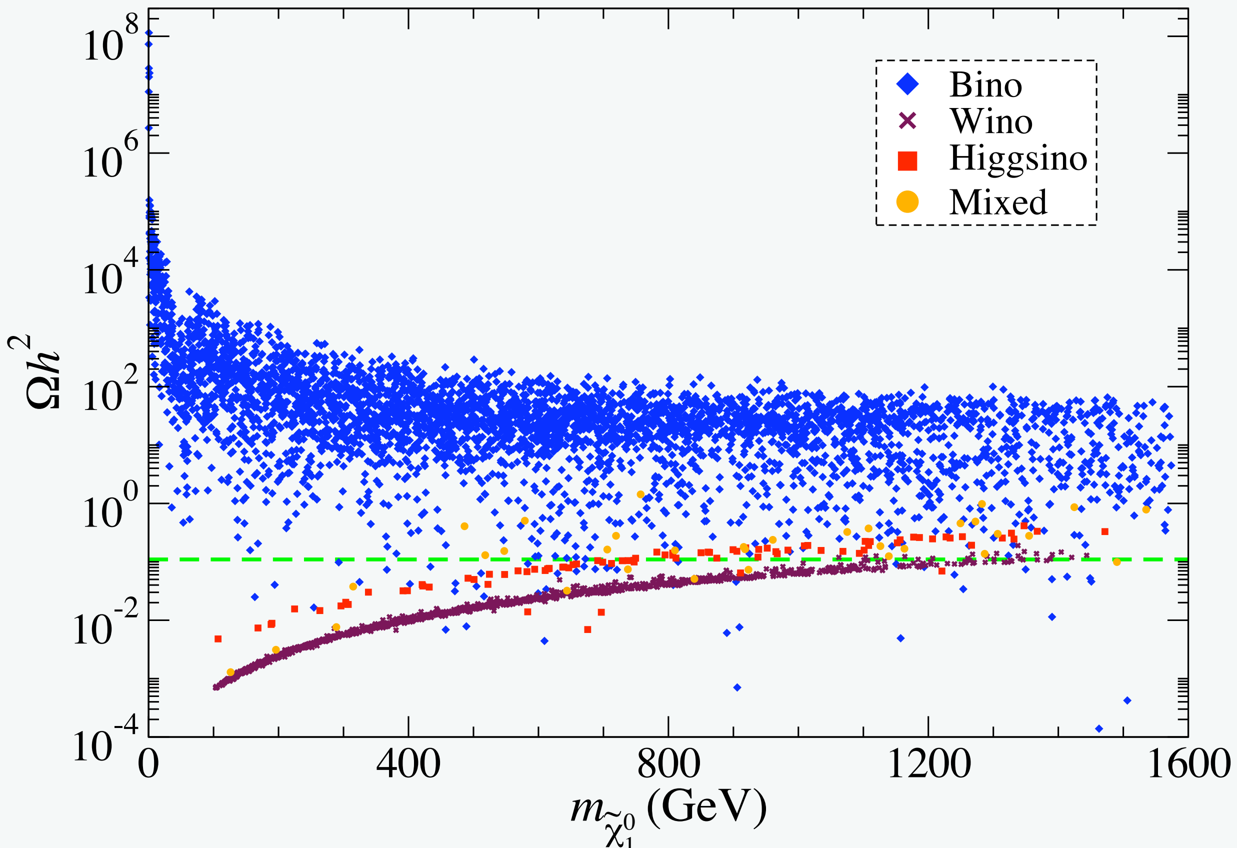
H. Baer, A. Box, H. Summy, arXiv:10052215

IF YOU ASSUME that DM is a single thermal relic of a conventional radiation-dominated early cosmology, then you want to be on the green dashed line



who is the SUSY dark matter?

- So perhaps the LSP is a very heavy bino-like neutralino
- Or a tuned mixture of bino-wino-higgsino-like neutralino
- Or some other superpartner,
- Or it isn't a thermal relic
- Or the cosmological history is more complicated,
- Or there are several dark matter particles...

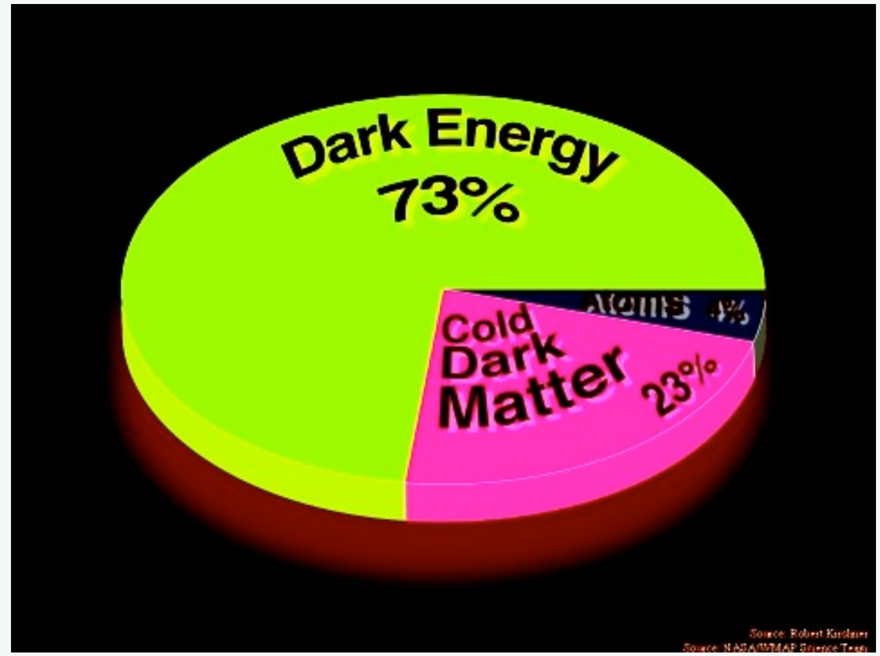


who is the SUSY dark matter?

Is there any reason to expect that the dark matter sector is less complicated than the visible matter sector?

D. Feldman, Z. liu, P. Nath, G. Peim, arXiv:1004.0649

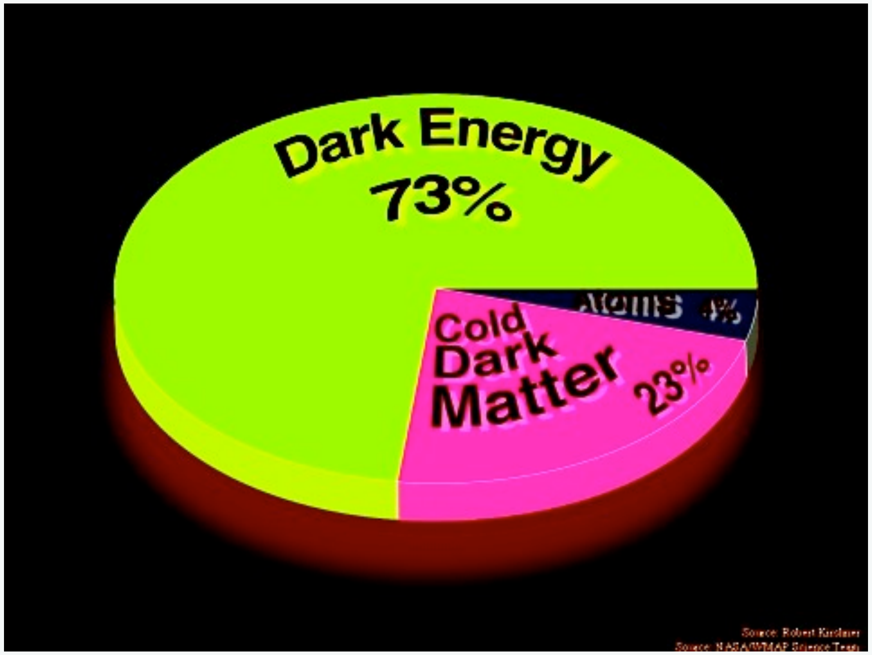
- Perhaps the dark sector has more than on stable component
- This might help to reconcile e.g. SUSY with direct and indirect DM detection "signals" from DAMA, COGENT, PAMELA, and constraints from CDMS, XENON, FERMI, etc



who is the SUSY dark matter?

Is there any reason to expect that the dark matter sector is less complicated than the visible matter sector?

D. Feldman, Z. liu, P. Nath, G. Peim, arXiv:1004.0649



- Perhaps the dark sector has more than on stable component
- This might help to reconcile e.g. SUSY with direct and indirect DM detection "signals" from DAMA, COGENT, PAMELA, and constraints from CDMS, XENON, FERMI, etc
- Simple MSSM extension: an extra U(1) charge, fermions and scalars charged under this, only weakly coupled to SM matter, and at least one is stable
- So perhaps SUSY gives a stable neutralino AND a stable exotic
- Or e.g. if $M_\chi < m_\phi < M_\chi + M_\psi$, then you get 4 different stable DM components: a Dirac fermion, a Majorana fermion, and two scalars.

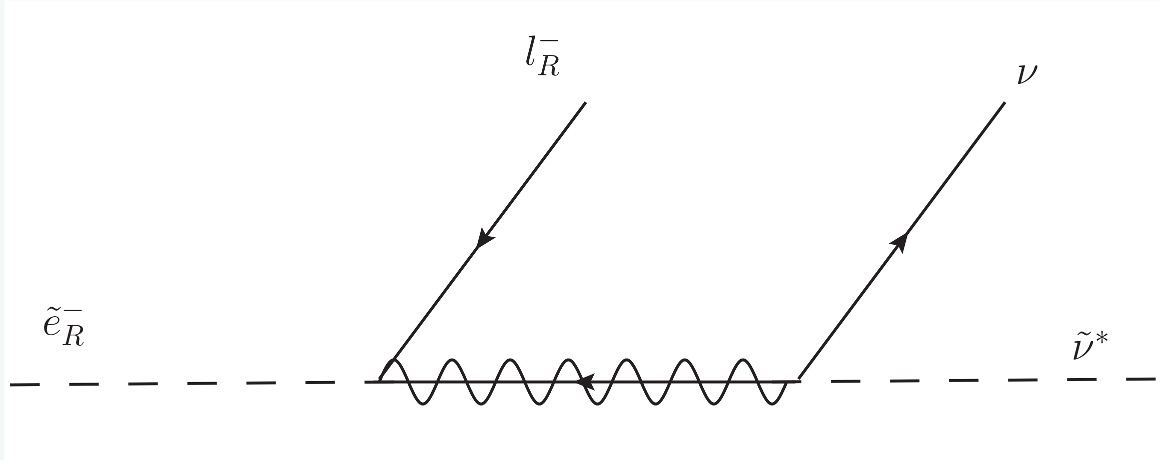
See also J. Fan, J. Thaler, L-T Wang, arXiv:1004.0008

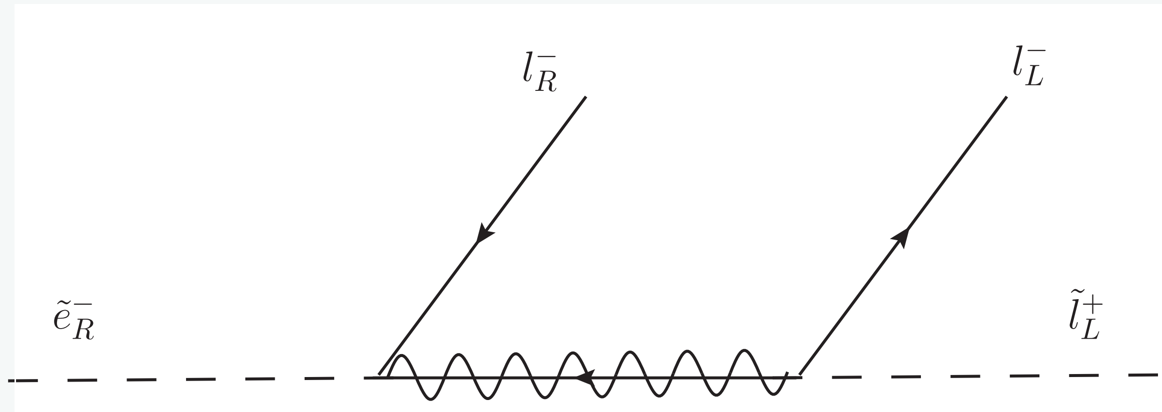
who is the SUSY dark matter?

At the LHC, we also care about who is the NLSP.

Might be long-lived (see Robin Erbacher's talk), or might have invisible decay

- sneutrino NLSP with, e.g. gravitino LSP can occur in gauge mediation and other SUSY models
- can't see the NLSP decay
- so you can be fooled as to who is your SUSY dark matter
- however this scenario is very leptophilic, so you will have lots of clean experimental handles to figure out the model





A. Katz, B. Tweedie, arXiv:0911.4132, arXiv:1003.5664

BSM look-alikes

- despite starting from different theoretical frameworks, some BSM models end up looking the same phenomenologically
- partly this is because they are trying to have the same "desirable" features
- while simultaneously getting around the bounds from existing data
- there are also some deep equivalences between certain classes of models, esp. warped extra dimensions models and models of new string gauge dynamics (AdS/CFT duality)

SUSY look-alikes

- There are lots of look-alikes just among SUSY models themselves

N. Arkani-Hamed, G. Kane, J. Thaler, L-T Wang, hep-ph/0512190

- But there are also non-SUSY frameworks that produce models phenomenologically similar to terascale SUSY with conserved R parity and neutralino LSPs:

Universal Extra Dimensions (UED) with conserved KK parity

Little Higgs models (LH) with conserved T parity

SUSY look-alikes

Universal Extra Dimensions (UED) with conserved KK parity

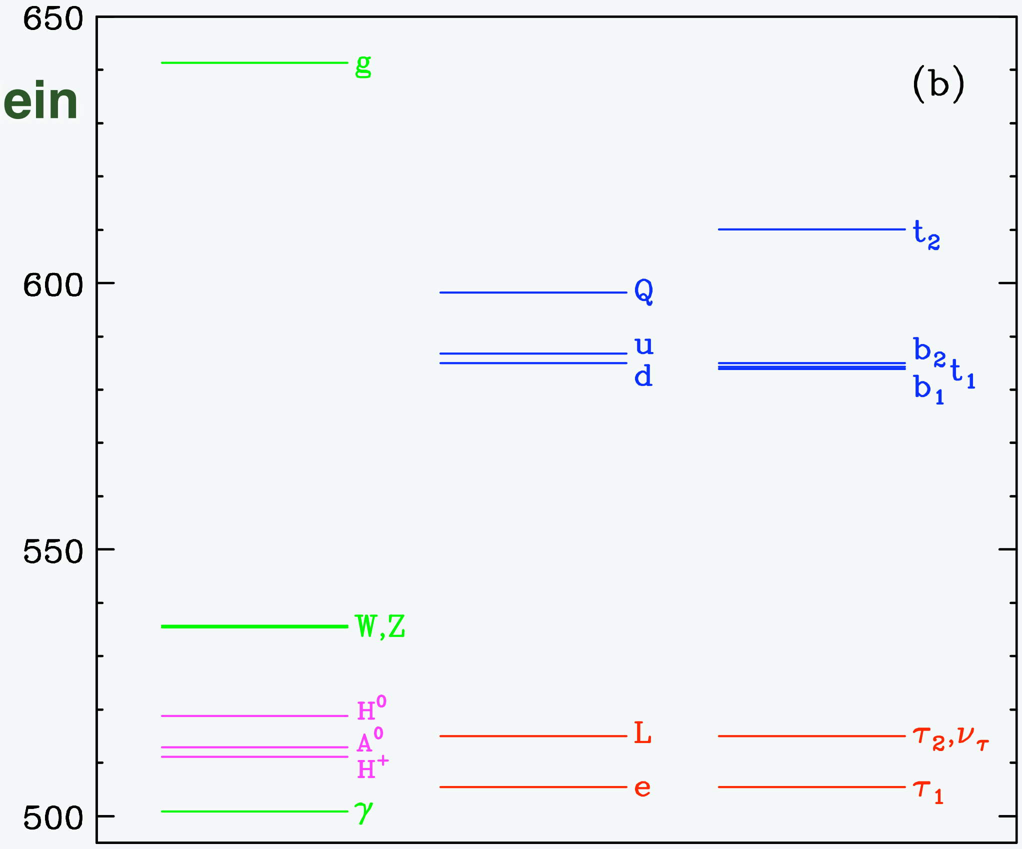
- There are one or two flat extra dimensions
- They have finite extent of order inverse TeV
- SM particles probe the full 5d (or 6d) bulk, but may also have couplings localized on the boundaries
- SM particles have heavier Kaluza-Klein partners

Appelquist, Cheng, Dobrescu (2000)

Cheng, Matchev, Schmaltz (2002)

Servant, Tait (2002)

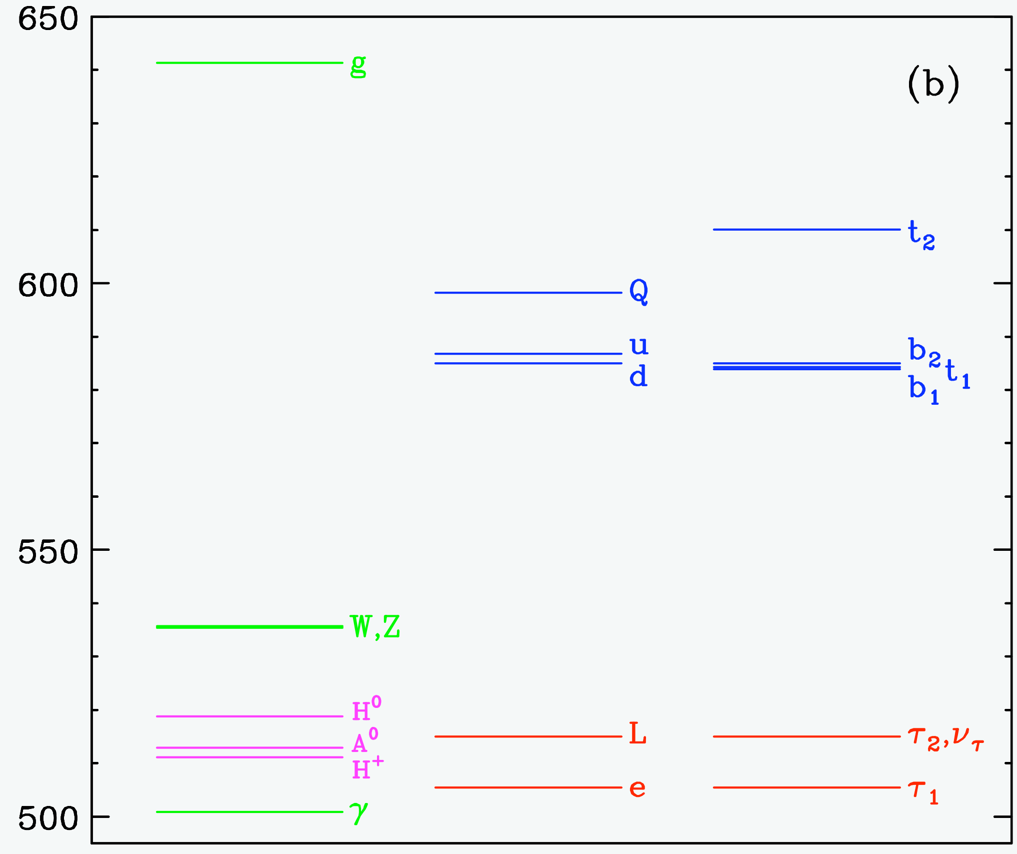
B. Dobrescu, D. Hooper, KC Kong, R. Mahbubani arXiv:0706:3409



SUSY look-alikes

Universal Extra Dimensions (UED) with conserved KK parity

- A discrete remnant of 5d momentum conservation, KK parity, keeps the lightest KK partner (LKP) stable
- The LKP is naturally weakly interacting, a good DM candidate
- e.g. LKP is spin 1 or spin 0 KK partner of the photon



A. Datta, KC Kong, K. Matchev, arXiv:1002.4624

SUSY look-alikes

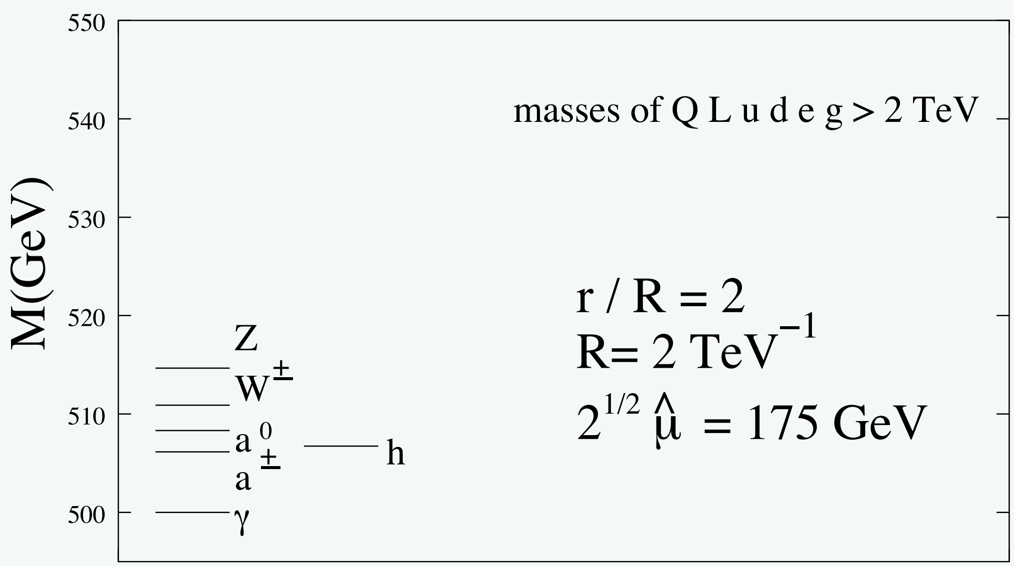
What's new with UED?

- More models! minimal UED extended to "non-minimal" UED, "split" UED, with different KK partner spectra

T. Flacke, A. Menon, D. Phalen, arXiv:0811.1598

KC Kong, S. Park, T. Rizzo, arXiv:1002.0602, arXiv:1004.4635

- More UED dark matter candidates!
- Could be KK partners of Higgs, LH neutrinos, RH neutrinos, Z, W_3, or the graviton



N. Shah and C. Wagner, hep-ph/0608140

J. Cembranos, J. Feng, L. Strigari, hep-ph/0612157

SUSY look-alikes

Little Higgs models (LH) with conserved T parity

- Basic idea: the Higgs is light because it is a PNGB of a big global symmetry
- The global symmetry is both spontaneously broken and explicitly broken because part of it is gauged to become the (parent of) the weak interaction gauge symmetry
- In effect, 1-loop quadratic divergences for the Higgs from SM particles are cancelled by loops with heavy SM "partners"
- To avoid problems with electroweak precision data, assume partners for all SM particles (more for the top) and that the partners are odd under some discrete "T parity"
- The LTP is a dark matter candidate...

Reviews: M. Schmaltz and D. Tucker-Smith, hep-ph/0502182

M. Perelstein, hep-ph/0512128

Missing energy look-alikes at the LHC

- At the 2011 Brookhaven Forum, B. Heinemann and R. Erbacher announce that ATLAS and CMS have >5 sigma signals in their inclusive missing energy searches
- How are you going to figure out that this is SUSY (what kind of SUSY?), Universal Extra Dimensions, Little Higgs, or something else?
- What is our strategy to disambiguate missing energy look-alikes?

Missing energy look-alikes at the LHC

First questions for a missing energy signal:

- How many invisible particles per event?
- Are they heavy or light?
- Are they associated with top, W, or Z decays?
- How many kinds of parent particles?
- How many kinds of decay chains?

We should be able to answer such questions
around the time of discovery

Missing energy look-alikes at the LHC

Eventually we want direct determinations of masses, charges, and spins, without inputing (BSM) theoretical assumptions

- Assuming you did a good job answering the questions on the previous slide, can use clever kinematic methods to do almost-model-independent mass determinations

  A. Barr, C. Lester, arXiv:1004.2732

  P. Konar, KC Kong, K. Matchev, M. Park, arXiv:0911.4126

- Charge determinations are not trivial, but at least some can be done (e.g. color octet versus color triplet versus color singlet)

- Direct spin and CP measurements are hard!

  L-T Wang, I. Yavin, arXiv:0802.2726

- Need to pin down topologies, decay chains, charges and masses first, then analyze lots and lots of data...

  See e.g. O. Gedalia, S. Lee, G. Perez, arXiv:0901.4438

We should be able to get most of this done in ~ a decade

Missing energy look-alikes at the LHC

Model-dependent analysis:

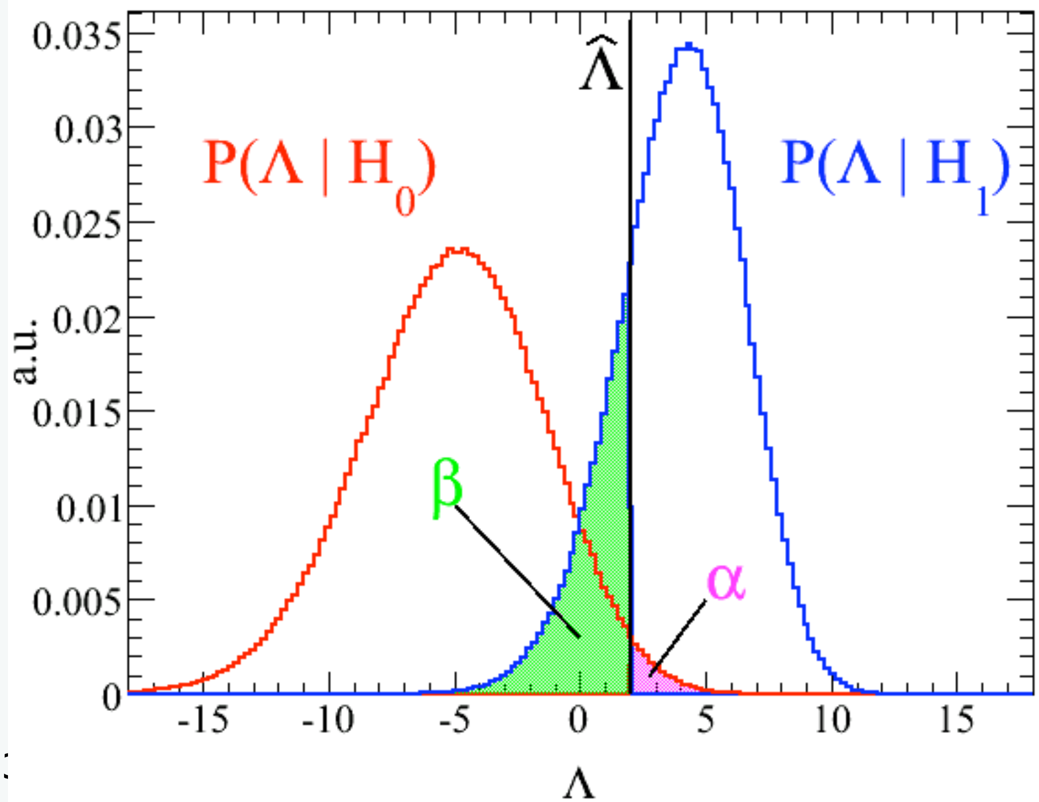
- Post-discovery you would like to quickly collapse the vast theory space of BSM models down to something managable

- An efficient method is simple hypothesis testing based on likelihood ratios based on matrix elements of benchmark BSM model lines

- This amounts to discriminating based on non-trivial functions of spins, charges, and masses

- Doesn't necessarily require lots of data or fancy precision analysis

Neyman-Pearson (NP) simple hypothesis test



Missing energy look-alikes at the LHC

SUSY (pMSSM with R parity) versus Little Higgs with T Parity

J. Hubisz, J. L., M. Pierini, M. Spiropulu, arXiv:0805.2398

G. Hallenbeck, M. Perelstein, C. Spethmann, J. Thom, J. Vaughn, arXiv:0812.3135

LH2 vs. NM4 [100 pb^{-1}]			
Variable	LH2	NM4	Separation
MET			
r(mT2-500)	0.16	0.05	4.87
r(mT2-400)	0.44	0.21	4.84
r(mT2-300)	0.75	0.54	3.49
r(Meff1400)	0.11	0.25	2.99
r(mT2-500/300)	0.21	0.09	2.98
r(M1400)	0.07	0.19	2.69
r(mT2-400/300)	0.58	0.40	2.48
r(HT900)	0.13	0.24	2.34
r(MET420)	0.48	0.37	2.00
r(mT2-500/400)	0.36	0.22	1.47

Table 21. Best discriminating ratios in the MET box, with separations in units of σ, for the comparison of LH2 vs.NM4, taking LH2 as the "data", assuming an integrated luminosity of 100 pb^{-1}.

LH2 vs. NM4 [1000 pb^{-1}]			
Variable	LH2	NM4	Separation
MET			
r(mT2-500)	0.16	0.05	14.11
r(mT2-400)	0.44	0.21	11.13
r(mT2-500/300)	0.21	0.09	8.52
r(Meff1400)	0.11	0.25	7.24
r(M1400)	0.07	0.19	6.57
r(mT2-300)	0.75	0.54	6.26
r(mT2-400/300)	0.58	0.40	5.77
r(HT900)	0.13	0.24	5.67
r(M1800)	0.02	0.07	4.82
r(MET420)	0.48	0.37	4.32

Table 36. Best discriminating ratios in the MET box, with separations in units of σ, for the comparison of LH2 vs.NM4, taking LH2 as the "data", assuming an integrated luminosity of 1000 pb^{-1}.

Conclusion

- The LHC will (we hope) discover something
- We have powerful tools to figure out the identity of what we find
- Most of this does not require 1 ab-1 or an ILC, but it will require (i) more work to get ready, (ii) multi-channel searches, (iii) luck